

ARMY RESEARCH LABORATORY



Evaluation of ALON for Cannon Window Application

by Richard A. Beyer and Henry Kerwien

ARL-TR-2358

October 2000

Approved for public release; distribution is unlimited.

20001212 019

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.

Army Research Laboratory

Aberdeen Proving Ground, MD 21005-5066

ARL-TR-2358

October 2000

Evaluation of ALON for Cannon Window Application

Richard A. Beyer

Weapons and Materials Research Directorate, ARL

Henry Kerwien

U.S. Army Armament Research, Development, and Engineering Center

Approved for public release; distribution is unlimited.

Abstract

In applying laser ignition to large-caliber cannons, a critical element is the window into the cannon chamber to admit the laser energy. This window must repeatedly withstand a particularly harsh environment of highly reactive, high temperature combustion products from the gun propellant at pressures up to 440 MPa (65,000 psi). Failure of the window can be caused by either thermal gradients in the window, mechanical force, or a combination. Previous successes with single-crystal sapphire have sometimes been limited by window deterioration modes suggestive of crystalline behavior. Samples of aluminum oxynitride spinel (ALON) have been fabricated in the same design as the standard sapphire windows and were qualified for gun testing. This process involves a series of experiments in a closed chamber, where gun propellant is burned to generate an environment similar to that inside the gun. Windows mounted in two methods have been tested. One of these windows has survived the full pregun test series with no visible damage.

Acknowledgments

The materials for these windows were provided by Randall Tustison of Raytheon Electronics. He also provided much encouragement and advice during the course of these studies. The ALON-E window was assembled by Steven McKnight of the U.S. Army Research Laboratory (ARL). Gary Gilde and Parimal Patel of ARL provided important advice and assistance with the analysis. Photomicrographs were obtained with the assistance of James Kleinmeyer of ARL.

INTENTIONALLY LEFT BLANK.

Table of Contents

	<u>Page</u>
Acknowledgments	iii
List of Figures	vii
List of Tables	vii
1. Introduction	1
2. Characterization of Cannon Environment	2
3. Window Fabrication	4
4. Tests	6
5. Observations and Analysis	7
6. Conclusions	10
7. References	11
Distribution List	13
Report Documentation Page	15

INTENTIONALLY LEFT BLANK.

List of Figures

<u>Figure</u>		<u>Page</u>
1. Simulation of Pressure-Time Behavior in a 155-mm Cannon	2	
2. Temperature Measurement on Breech Face During Firing.....	3	
3. Pressure and Temperature Measurement on Common Time Scale.....	4	
4. Configuration of Windows and Approximate Dimensions.....	5	
5. Pressure Record From Test No. 6 of ALON-M	6	
6. Photograph and Diagram Showing Damage to High-Pressure Face of ALON-M After Tests.....	8	
7. Images of Internal Damage to ALON-M Through Large Face.....	9	
8. ALON-M After Removal From Case	9	

List of Tables

<u>Table</u>		<u>Page</u>
1. Peak Pressures Recorded for Windows in Test Fixture	7	

INTENTIONALLY LEFT BLANK.

1. Introduction

Laser ignition of large-caliber cannons offers many potential advantages over conventional ignition systems [1]. Chief among these are increased firing rate and reduced complexity of design. Most proposed designs use an external laser, which requires a window to pass the light energy through the cannon wall. Typical 155-mm cannons currently used or under development use projectiles and propellant which are loaded separately into the gun breech. The propellant is contained in a bag or case, which is consumed during the gun function. Thus, the normal approach is to have a window which is incorporated into the breech of the gun and must therefore survive multiple firings of the weapon.

While developing the window which is currently in use for research and developmental cannons in the Army, many designs were attempted with mixed success. A recurring phenomenon with the early failures that occurred was that they were often associated with crystal behavior such as twining or crystal plane slippage. These modes of degradation are noncatastrophic in the sense that the pressure integrity of the cannon breech remains in place. However, they do result in reduced transmission of light into the cannon and loss in ignition system efficiency. Because of the association of single crystal behavior with the most common degradation modes, there has been an effort to identify potential candidate replacements among other classes of materials.

In addition to degradation due to the loss of transmission through the crystal, the sapphire can also suffer slower, long-term damage to the hot face which suggests chemical attack. This effect results in a translucent layer developing after a large number of cycles. This degradation mechanism is not addressed in the limited number of tests of the present work.

Aluminum oxynitride spinel (ALON) is currently under evaluation at the U.S. Army Research Laboratory (ARL) as a candidate for transparent armor [2]. A small sample of ALON was made available after determining that it possessed sufficient strength and other characteristics required to perform as a window material in the cannon systems. Three windows

were fabricated; tests to simulate the gun environment were performed on two of them. The details and conclusions of these tests are described in this report.

2. Characterization of Cannon Environment

During the interior ballistic cycle of a modern 155-mm cannon, propellant is burned at flame temperatures near 2300 °C and pressures of 350 MPa (50 Kpsi) or more. The pressure and highly turbulent combustion environment result in thin boundary layers and highly effective heat transfer to the breech wall. The pressure in a cannon is a well-characterized parameter through both measurement and highly sophisticated computer simulation. The pressure-time profile near the breech from a simulation of a generic 155-mm cannon is shown in Figure 1.

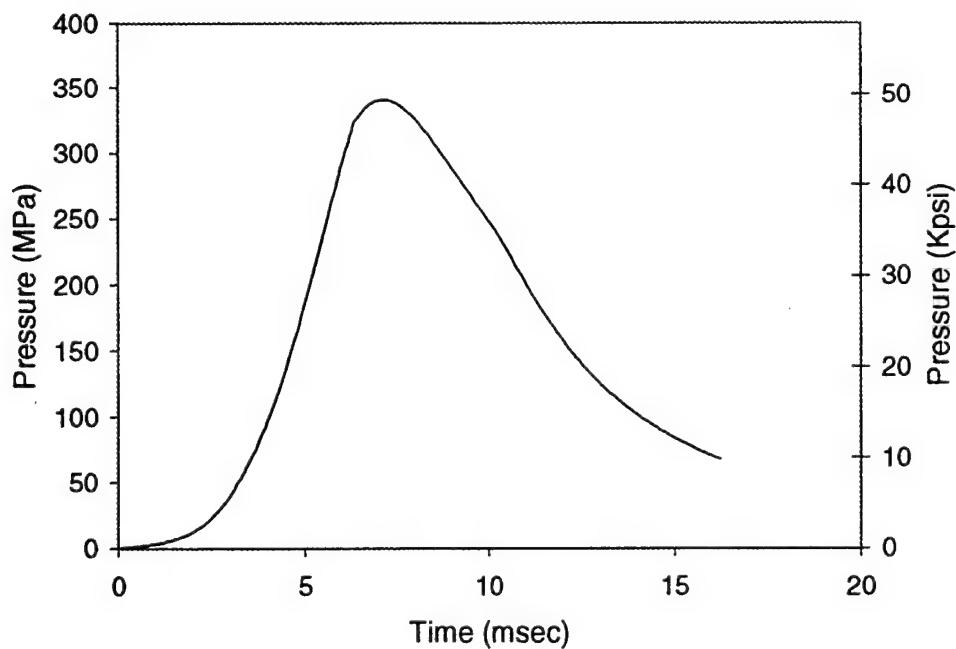


Figure 1. Simulation of Pressure-Time Behavior in a 155-mm Cannon.

Heat transfer measurements to cannon tube walls are typically concerned with metal erosion at regions in the forward parts of the breech. Because of the differences in flow velocity at the breech wall (where the window is mounted), these are of little value in determining the environment in which the window must survive. As a part of the window development program,

Bundy [3] made one series of measurements of the temperature history on the breech wall. Although this study was subject to the many problems that can affect instrumentation in this harsh environment, a limited number of temperature-time records were recorded that better define the window environment. One of these is shown as Figure 2. Note that the time scale of the temperature pulse is much longer than that of pressure. Probably, residual heat from the adjacent cannon wall, as well as hot gases in the breech, slow the cooling rate of the temperature probe. However, there is no claim that this profile exactly mimics the window surface environment during a cannon firing. Bundy's report suggests that the peak temperature may be significantly higher than measured.

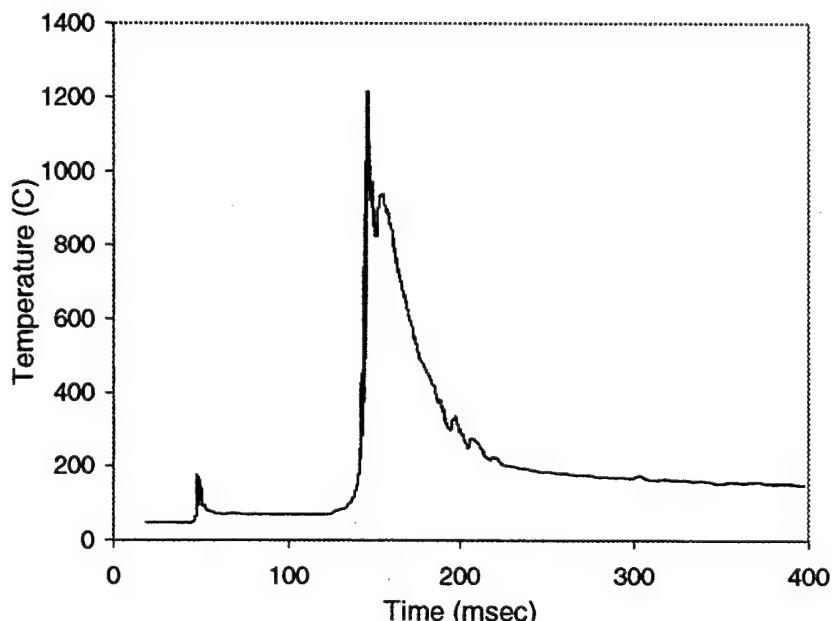


Figure 2. Temperature Measurement on Breech Face During Firing [3].

In order to compare the pressure and temperature profiles on a similar time scale, data from these two figures are shown in Figure 3 with a time shift to place the nearly coincident rises. As can be seen in the figure, the pressure event and the initial portion of the temperature record are similar in duration.

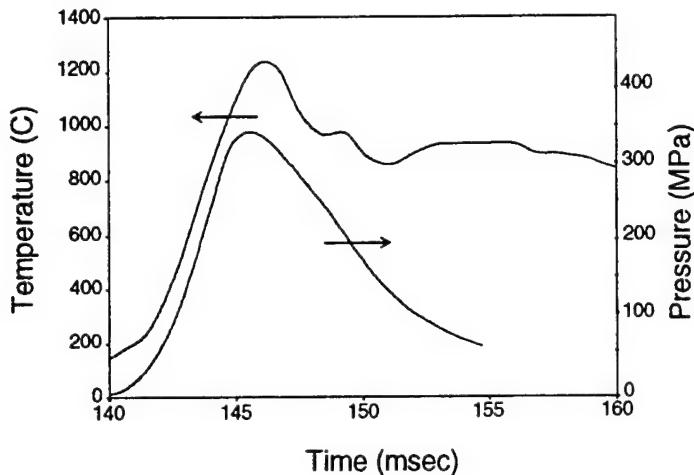


Figure 3. Pressure and Temperature Measurement on Common Time Scale.

The pressure experienced by a window does not present a great design challenge for sapphire (or ALON). Also, the peak temperature measured of near 1200 °C is within the temperature range where sapphire might readily be used, especially for a short time. The failures of test windows suggest that the combination of these two conditions simultaneously provides a unique challenge to survival.

3. Window Fabrication

The ALON samples used in these experiments were provided by Raytheon Electronic Systems, Lexington, MA. Three windows were fabricated by Kigre, Inc., Hilton Head, SC, into the conical design that has been used successfully with single crystal sapphire. The basic shape is shown in Figure 4. These windows are usually fabricated with all sides fully polished. In order to minimize cost, these ALON windows were polished on the optical surfaces only; the sides were ground. This general configuration is not unlike those found in earlier high-pressure window designs, such as those of Stromberg and Schock [4].

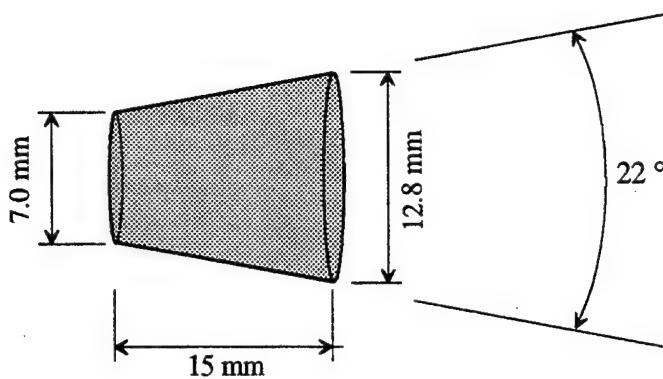


Figure 4. Configuration of Windows and Approximate Dimensions.

Two ALON windows were mounted into threaded steel cases that allowed testing in standard fixtures and cannons. The first window was assembled using a ductile metal sleeve interface between it and the case. This technique works well with the single crystal sapphire windows. In this process, after the clean components are put in place, the window is pressed into the case with approximately 9 kN (1 ton) of force. This force serves to seat the window into the soft metal and forms a low-pressure seal between the components. During this pressing portion of the process, the ALON windows showed significant damage around the edge of the large end. The remaining clear aperture was larger than the small aperture, so tests on one of these windows proceeded. The window seated in metal is referred to as ALON-M.

Because of the damage to the first window assembled, adhesive was used to fix the second window which was tested. This window was degreased and fastened into the case using a high-performance aerospace grade primer and epoxy. The bond length of the epoxy was minimized and thought to be approximately 0.025 mm (0.001 in). The assembly was cured at elevated temperature. Although epoxy is an attractive assembly method, in some earlier tests the sapphire windows showed limited durability; the epoxy eroded after the hot combustion gases penetrated into the window-case interface. However, as a test of material suitability, this mounting technique should prove satisfactory. This window is referred to as ALON-E.

4. Tests

Windows that will be used in gun or other highly demanding environments are typically exposed to a series of pressures of increasing magnitude. This approach allows the window to become fully seated in the ductile metal liner while confidence is established in the particular assembly. The pressure for this phase of testing is generated by burning a charge of propellant in a closed vessel with a capacity of approximately 1 liter. By varying the amount of propellant charge, the pressure history of the window assembly is varied. The maximum pressure for this test phase is usually around 400 MPa (60 Kpsi), which is comparable to the pressure a window would normally experience in a cannon. (Higher pressures can be obtained for safety factors, as required.) Although the flow of the hot gases is not the same as in a cannon, due to the fixed volume, the pressure and temperature provide an excellent simulation of the cannon breech environment. The pressure-time record for the final test of window ALON-M is shown in Figure 5. The total decay time of the pressure pulse is slightly more than in a cannon, but the rise time and peak pressure are well-simulated. During these tests, the window is directly exposed to the burning propellant.

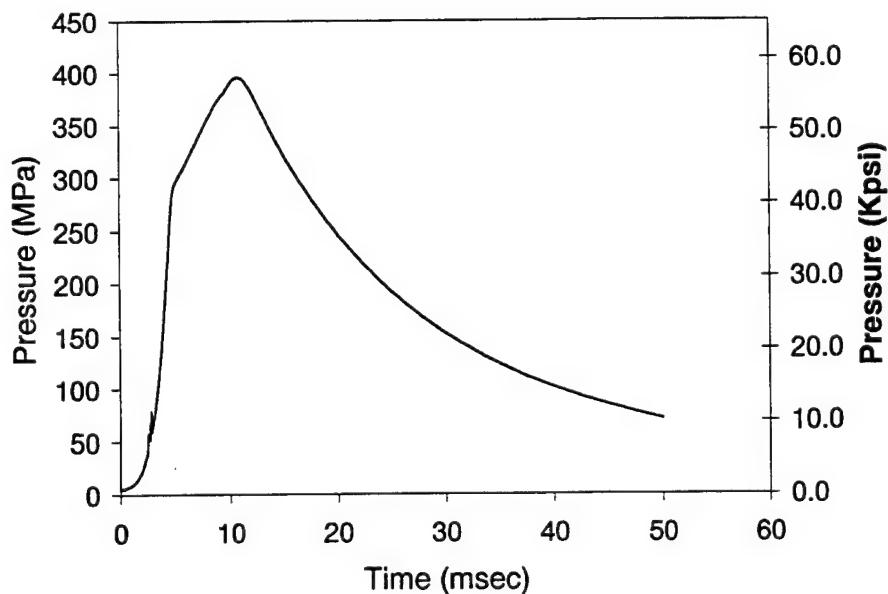


Figure 5. Pressure Record From Test No. 6 of ALON-M.

The peak pressures recorded for these two windows are shown in Table 1. Tests were terminated on ALON-M after the sixth test when the subsurface damage was noted. Because this damage was internal and it was surface damage that was most closely monitored, it may have begun to fail at a lower pressure. The target pressure for test no. 6 of window ALON-E was between 55 and 60 Kpsi.

Table 1. Peak Pressures Recorded for Windows in Test Fixture

Test No.	ALON-M		ALON-E	
	MPa	psi	MPa	psi
1	63	9,184	64	9,312
2	76	11,008	93	13,440
3	122	17,664	122	17,632
4	235	34,112	240	34,848
5	312	45,280	314	45,568
6	396	57,440	No data	No data
7	—	—	376	54,592
8	—	—	402	58,240

5. Observations and Analysis

The response of the two windows was considerably different. Window ALON-E survived the full battery of qualifying tests with no evidence of degradation. Because of sapphire's history of damage at the hot-face edge due to loss of support as the epoxy erodes, careful inspection was made of this region. It does appear possible that small fragments of the ALON may have been lost. The magnitude of the possible damage is small and inconclusive with this small number of tests. Overall, the performance of this window is satisfactory within the limits tested. The evidence suggests that this window and single-crystal sapphire would survive in a cannon.

Window ALON-M showed damage in two regions. The hot-face damage increased in area by more than a factor of two. As shown in Figure 6, a sufficient center aperture remains clear; this window would still be usable if this were the only damage. However, since this damage is from a limited number of cycles, it is not likely that this method of seating is appropriate for ALON. Thus, this damage alone would probably be sufficient to rule out ALON seated in metal as a useful configuration for our purposes.

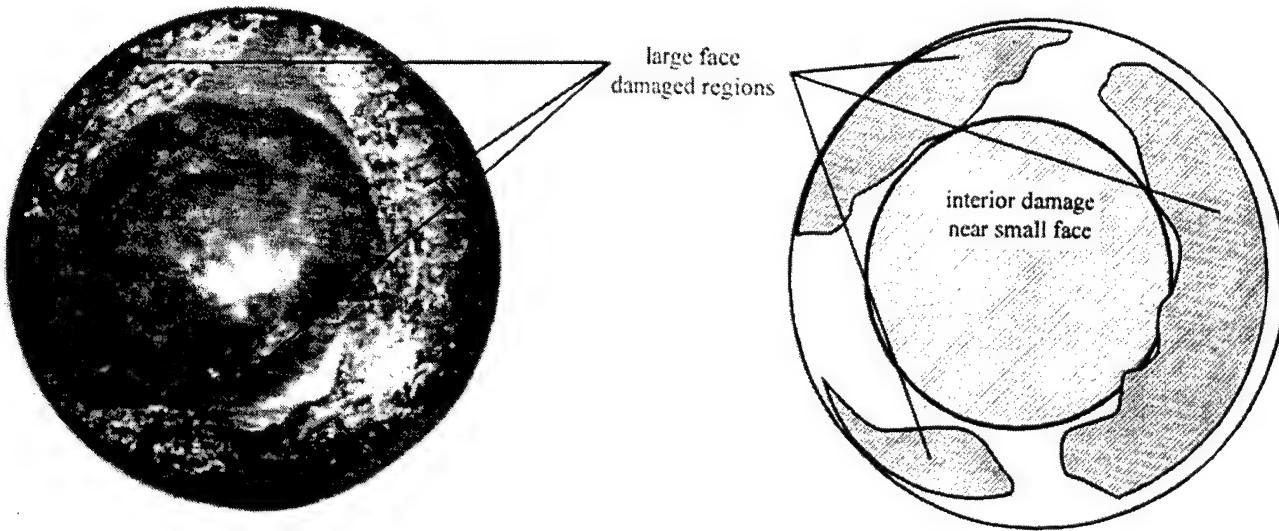


Figure 6. Photograph (Left) and Diagram (Right) Showing Damage to High-Pressure Face of ALON-M After Tests.

In addition to the surface damage, the window lost transparency in a region close to the small (cold) face. Two images of this damage are shown here, as observed from the large (hot) face. These images are the same as Figure 6, with the focus moved down to the damage plane and the field of view decreased. Figure 7a shows the full clear aperture of about 7 mm. Figure 7b is a magnified portion of the center of that same region. In addition, images were recorded using crossed polarizers to identify regions of high strain. These images are not included here. Evidence of internal strain was observed near the smaller face. It covered less than 25% of the window cross section at that end. This residual strain was consistent with the damage to the window.

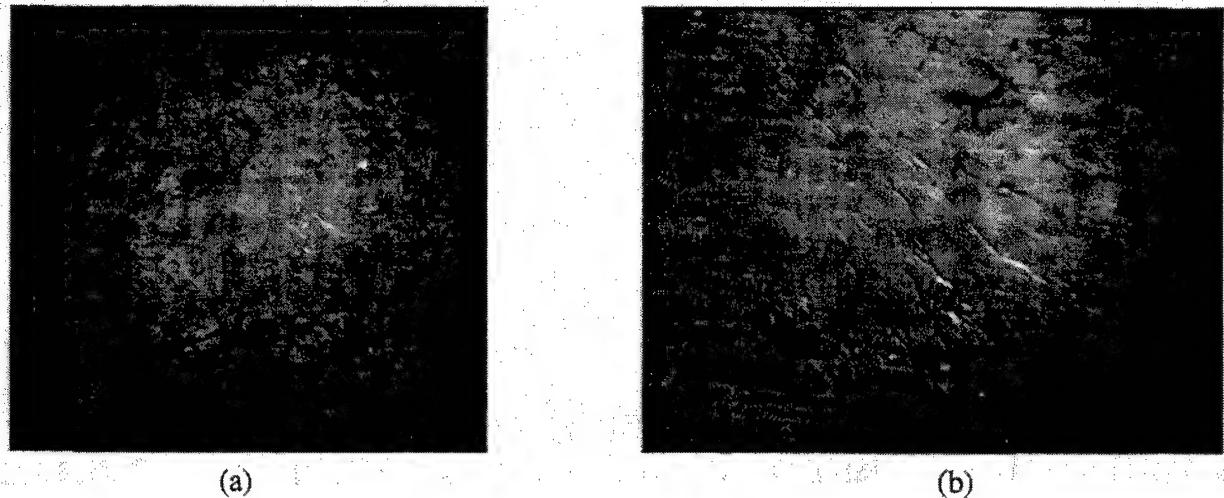


Figure 7. Images of Internal Damage to ALON-M Through Large Face: (a) Full Aperture and (b) Closer View of Center Portion.

The window was pushed out of the case so that the window, case, and metal interface could be examined in detail. It fractured cleanly into three parts, as shown schematically in Figure 8. Two small slices were broken from the smaller end. Both breaks were nearly normal to the window's axis of symmetry. The lower break was quite flat. The other was curved slightly toward the large face. The thickness of these pieces was measured at approximately 1.7 and 2.2 mm, respectively.

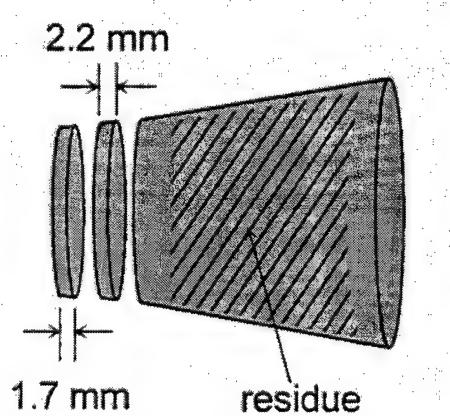


Figure 8. ALON-M After Removal From Case.

Residue from the propellant combustion products penetrated both sides of the soft metal seal to near the region of the fractures. It is not uncommon for gas penetration into very small cracks to be observed in objects tested under these conditions. (This is the source of attack on the adhesive when that method of mounting is used.)

Measurement of the angles of the window (exterior) and case (interior) confirmed that they were within the limits that would normally be considered satisfactory with sapphire. However, the soft metal sleeve showed clear deformation and loading only at the region of the fracture. An examination of the interior shape and finish of the case seating area has revealed no major condition that would have made this case unacceptable for mounting a sapphire window.

Since sapphire windows have not been failing in this mounting configuration, insufficient evidence is available to compare these postmortem components with those from standard sapphire components. However, the fabrication of this window was not by the usual sapphire fabricator. Thus, it is not totally conclusive that this mounting technique will not work well with ALON. It is interesting to note that the postmortem observations show that the hot end of the window was not well-seated into the soft metal, as indicated by the residue deposits. Thus, the amount of force causing the "chipping" of that surface is thought to have been smaller as mounted here than if the window were seated into the metal in a manner sufficient to provide a high-pressure seal. It appears that even with the forces present, the window experienced tensile forces at the hot face that caused the observed cracking and spalling.

6. Conclusions

The tests in this report strongly indicate that properly mounted ALON will survive the cannon environment. Further tests are required to study the long-term surface response to the gun environment and to compare any degradation to that of crystalline sapphire. The performance of ALON also suggests that other related materials, such as spinel ($MgAl_2O_4$), might be useful in this environment as well. These materials might be explored for potential advantages characteristic of their chemical composition.

7. References

1. Barrows, A. W., B. E. Forch, R. A. Beyer, A. Cohen, and J. E. Newberry. "Laser Ignition in Guns, Howitzers, and Tanks: The LIGHT Program." ARL-TR-62, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, 1993.
2. Swab, J. J., J. C. LaSalvia, G. A. Gilde, P. J. Patel, and M. J. Motyka. "Transparent Armor Ceramics: ALON and Spinel." 23rd Annual Conference on Composites, Advanced Ceramics, Materials and Structures, unpublished data.
3. Bundy, M. "Thermal Response of Sapphire to Propellant Combustion." ARL-TR-1654, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, 1998.
4. Stromberg, H. D., and R. N. Schock. "A Window Configuration for High Pressure Optical Cells." *Rev. Sci. Instrum.*, vol. 41, pp. 1880–1881, 1970.

INTENTIONALLY LEFT BLANK.

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	DEFENSE TECHNICAL INFORMATION CENTER DTIC DDA 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218	1	DIRECTOR US ARMY RESEARCH LAB AMSRL D D R SMITH 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	HQDA DAMO FDT 400 ARMY PENTAGON WASHINGTON DC 20310-0460	1	DIRECTOR US ARMY RESEARCH LAB AMSRL DD 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	OSD OUSD(A&T)/ODDDR&E(R) R J TREW THE PENTAGON WASHINGTON DC 20301-7100	1	DIRECTOR US ARMY RESEARCH LAB AMSRL CS AS (RECORDS MGMT) 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	DPTY CG FOR RDA US ARMY MATERIEL CMD AMCRDA 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001	3	DIRECTOR US ARMY RESEARCH LAB AMSRL CI LL 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	INST FOR ADVNCD TCHNLGY THE UNIV OF TEXAS AT AUSTIN PO BOX 202797 AUSTIN TX 78720-2797		<u>ABERDEEN PROVING GROUND</u>
1	DARPA B KASPAR 3701 N FAIRFAX DR ARLINGTON VA 22203-1714	4	DIR USARL AMSRL CI LP (BLDG 305)
1	NAVAL SURFACE WARFARE CTR CODE B07 J PENNELLA 17320 DAHLGREN RD BLDG 1470 RM 1101 DAHLGREN VA 22448-5100		
1	US MILITARY ACADEMY MATH SCI CTR OF EXCELLENCE DEPT OF MATHEMATICAL SCI MADN MATH THAYER HALL WEST POINT NY 10996-1786		

NO. OF
COPIES ORGANIZATION

ABERDEEN PROVING GROUND

20 DIR USARL
 AMSRL WM BD
 B E FORCH
 W R ANDERSON
 S W BUNTE
 C F CHABALOWSKI
 A COHEN
 R DANIEL
 D DEVYNCK
 R A FIFER
 B E HOMAN
 A J KOTLAR
 K L MCNESBY
 M MCQUAID
 M S MILLER
 A W MIZIOLEK
 J B MORRIS
 R A PESCE-RODRIGUEZ
 B M RICE
 R C SAUSA
 M A SCHROEDER
 J A VANDERHOFF

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)			2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
			October 2000	Final, Apr 98 - Mar 99
4. TITLE AND SUBTITLE			Evaluation of ALON for Cannon Window Application	
6. AUTHOR(S)			Richard A. Beyer and Henry Kerwien*	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)			U.S. Army Research Laboratory ATTN: AMSRL-WM-BD Aberdeen Proving Ground, MD 21005-5066	
8. PERFORMING ORGANIZATION REPORT NUMBER			ARL-TR-2358	
9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
*U.S. Army Armament Research, Development, and Engineering Center Picatinny Arsenal, NJ 07806-5000				
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT			12b. DISTRIBUTION CODE	
Approved for public release; distribution is unlimited.				
13. ABSTRACT (Maximum 200 words)				
<p>In applying laser ignition to large-caliber cannons, a critical element is the window into the cannon chamber to admit the laser energy. This window must repeatedly withstand a particularly harsh environment of highly reactive, high temperature combustion products from the gun propellant at pressures up to 440 MPa (65,000 psi). Failure of the window can be caused by either thermal gradients in the window, mechanical force, or a combination. Previous successes with single-crystal sapphire have sometimes been limited by window deterioration modes suggestive of crystalline behavior. Samples of aluminum oxynitride spinel (ALON) have been fabricated in the same design as the standard sapphire windows and were qualified for gun testing. This process involves a series of experiments in a closed chamber, where gun propellant is burned to generate an environment similar to that inside the gun. Windows mounted in two methods have been tested. One of these windows has survived the full pregun test series with no visible damage.</p>				
14. SUBJECT TERMS			15. NUMBER OF PAGES	
ALON, window, laser ignition, cannon			19	
16. PRICE CODE				
17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT	
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL	

INTENTIONALLY LEFT BLANK.

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. ARL Report Number/Author ARL-TR-2358 (Beyer) Date of Report October 2000

2. Date Report Received _____

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.)

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.)

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate.

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.)

Organization

CURRENT
ADDRESS

Name _____ E-mail Name _____

Street or P.O. Box No.

City, State, Zip Code

7. If indicating a Change of Address or Address Correction, please provide the Current or Correct address above and the Old or Incorrect address below.

Organization

OLD
ADDRESS

Name _____

Street or P.O. Box No.

City, State, Zip Code

(Remove this sheet, fold as indicated, tape closed, and mail.)
(DO NOT STAPLE)